SC LINAC CAVITY PHYSICS

P. Kneisel

Oct. 31-Nov. 2, 2000

Cavities - Concept

Because of a very tight schedule for construction of the sc linac, the following principles were applied:

- Use performance requirements, which have already been demonstrated in other accelerators
- Use existing and proven designs
- Seek help from experts in other SRF labs and projects through collaborative agreements

There is no “glory” in re-inventing the “wheel” and make incremental improvements. The “glory” and challenge lies in meeting cost and schedule requirements

Prototyping Effort (cont'd)

The deliverables in this effort are:

- Four $\beta = 0.61$ niobium cavities, performance tested
- Two $\beta = 0.81$ niobium cavities, performance tested
- One copper cavity each of both types for HOM coupler development
- Ten KEK type high power couplers, modified for 805 MHz and tested and 8 HOM couplers of the TESLA/Saclay type, tested
- One $\beta = 0.61$ cryomodule, complete with tuners, tested
- A procurement package for the purchase of $\beta = 0.61$ cryomodules
- A procurement package for the purchase of $\beta = 0.81$ cryomodules
- A single cell $\beta = 0.61$ niobium cavity for multipacting studies
- A single cell $\beta = 0.61$ niobium cavity with welded-on HOM couplers

"External" Collaborations

SUBJECT	COLLABORATION
Cavity design	INFN Milan C. Pagani, P. Pierini, D. Barni, G. Ciovati
Mechanical Modes, Lorentz Force Detuning Mechanical Tuning	D. Schrage, LANL N. Ouchi, JAERI
Fundamental Power Coupler	KEK K. Saito, S. Noguchi, S. Mitsunobu
Higher Order Modes	DESY J. Sekutowicz
HOM Coupler	DESY J. Sekutowicz
Multipacting (Cavity)	INFN Genoa R. Parodi
Multipacting (Cavity, Coax Coupler)	R. Nevanlinna Institute, Univ. of Helsinki P. Ylae-Oijala

Cavity Design Criteria

- Cell-to-cell coupling: >1.5 %
- E_{peak} < 27.5 MV/m @ E_{acc} = 10.2 MV/m, $\beta = 0.61$
- H_{peak} < 60 mT @ E_{acc} = 10.2 MV/m, $\beta = 0.61$
- Lorentz Force Detuning Coefficient:

  K < (2 +/- 1) [Hz/(MV/m)^2]
- Q_{ext} for input coupler: Q_{ext} ~7 x 10^5
- Slope angle of side wall: >6^0

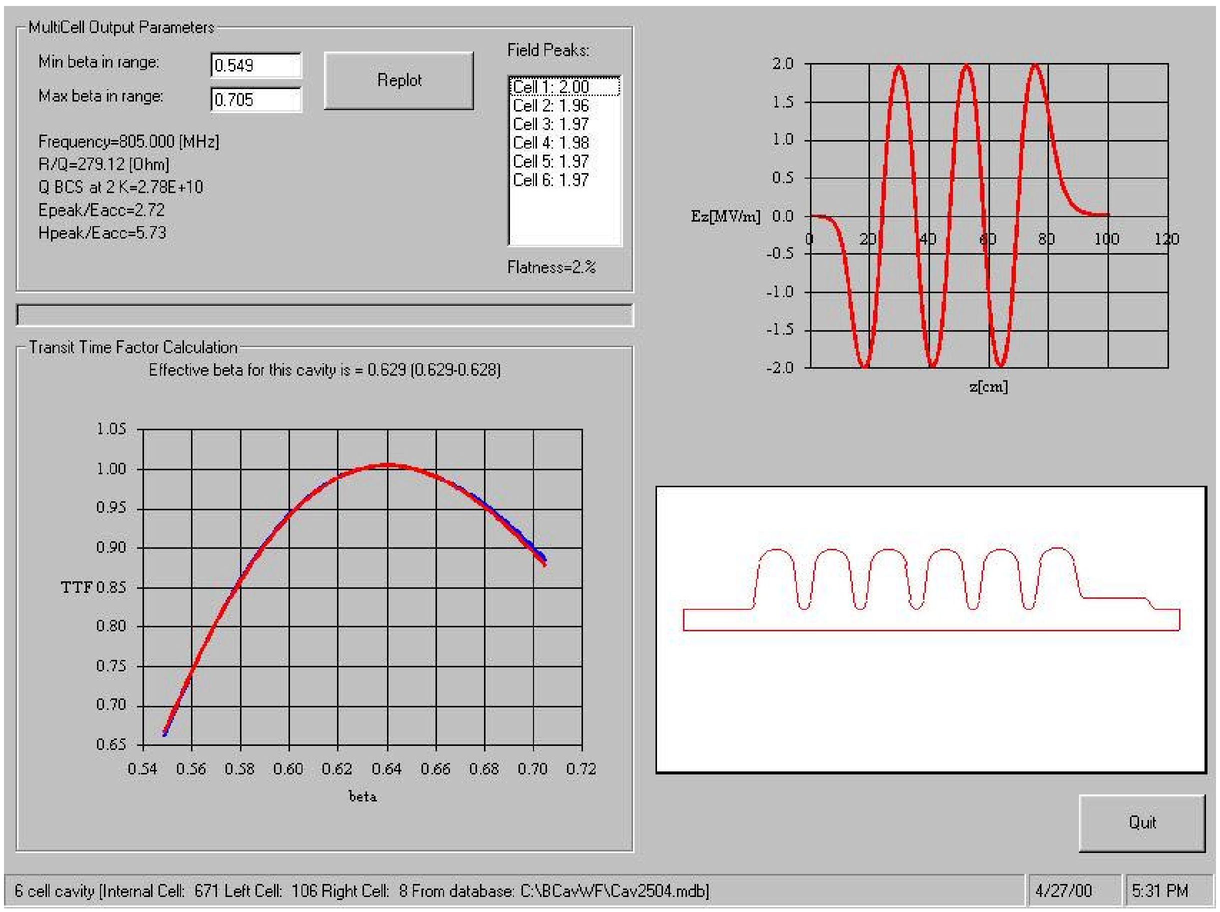
Cavities, b = 0.61

The cavity parameters for the $\beta = 0.61$ cavity have been established during a workshop at JLab April 12-13, 2000 (calculations by INFN, Milano-group), 4 die design

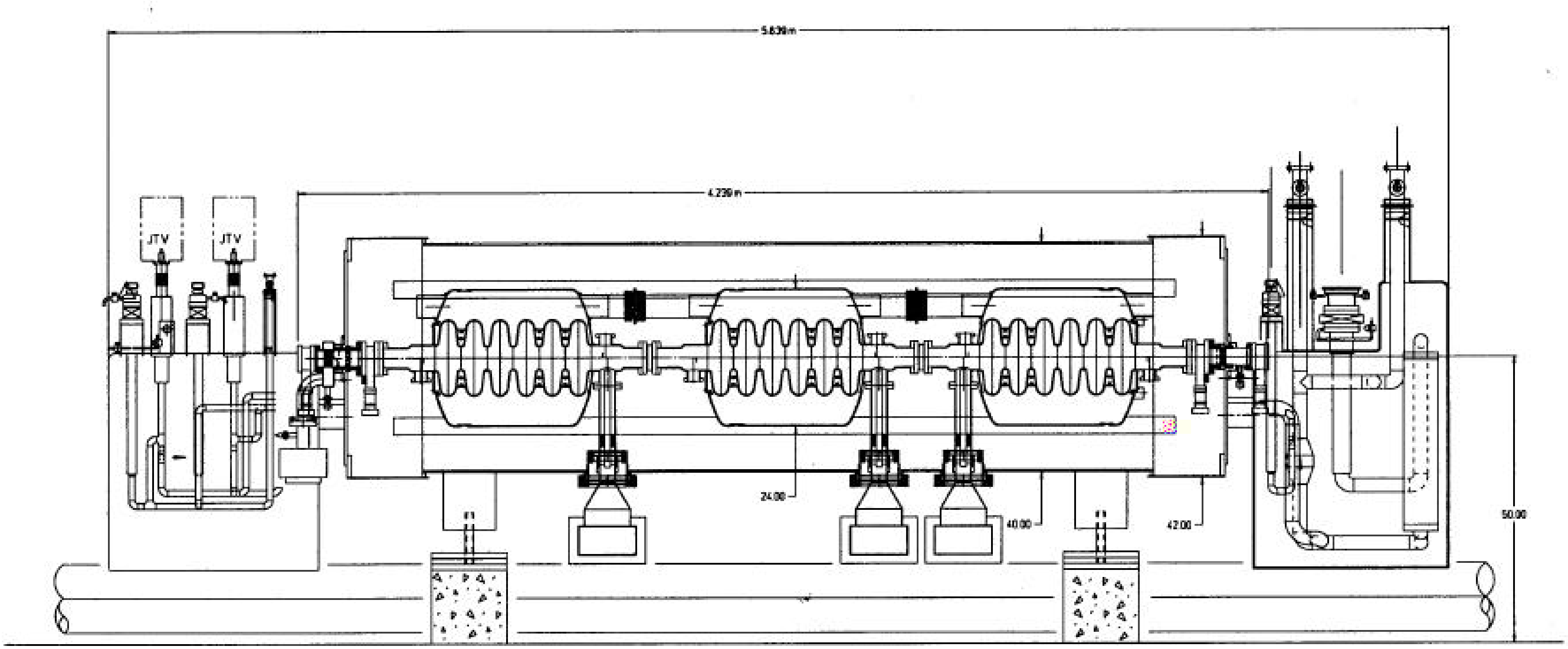
E_p / E_{acc}		2.69 (2.63 for inner cell)
B_p / E_{acc} [mT/(MV/m)]		5.64 (5.44 for inner cell)
R / Q [Ω]	295	
G [Ω]		214
K [%]		1.53
Q_{BCS} @ 2K [10^9]		27.36
Frequency [MHz]		805.082
Field Flatness [%]	1	
Lorentz-force detuning		KL70 = -2.9 Hz/[(MV/m)^2
		KL80 = -3.4 Hz/[(MV/m)^2
		Nb thickness = 3.8 mm

Cavity $\beta = 0.61$

- Electromagnetic Design (INFN, “Build Cavity”)



SNS Medium Beta Cryomodule

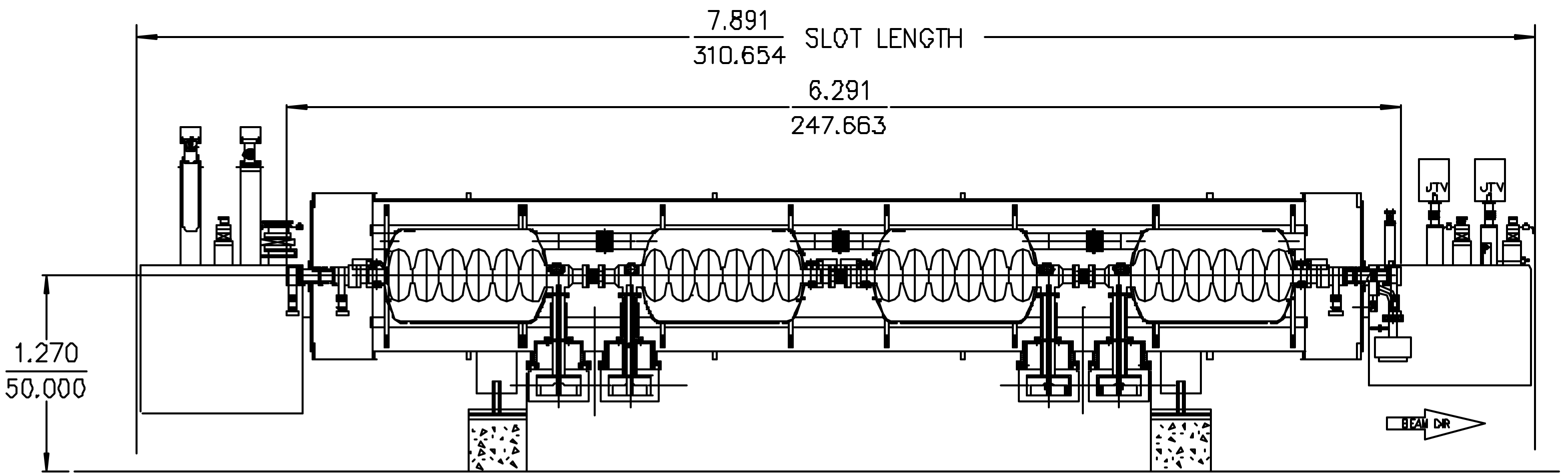


Cavity $\beta = 0.81$

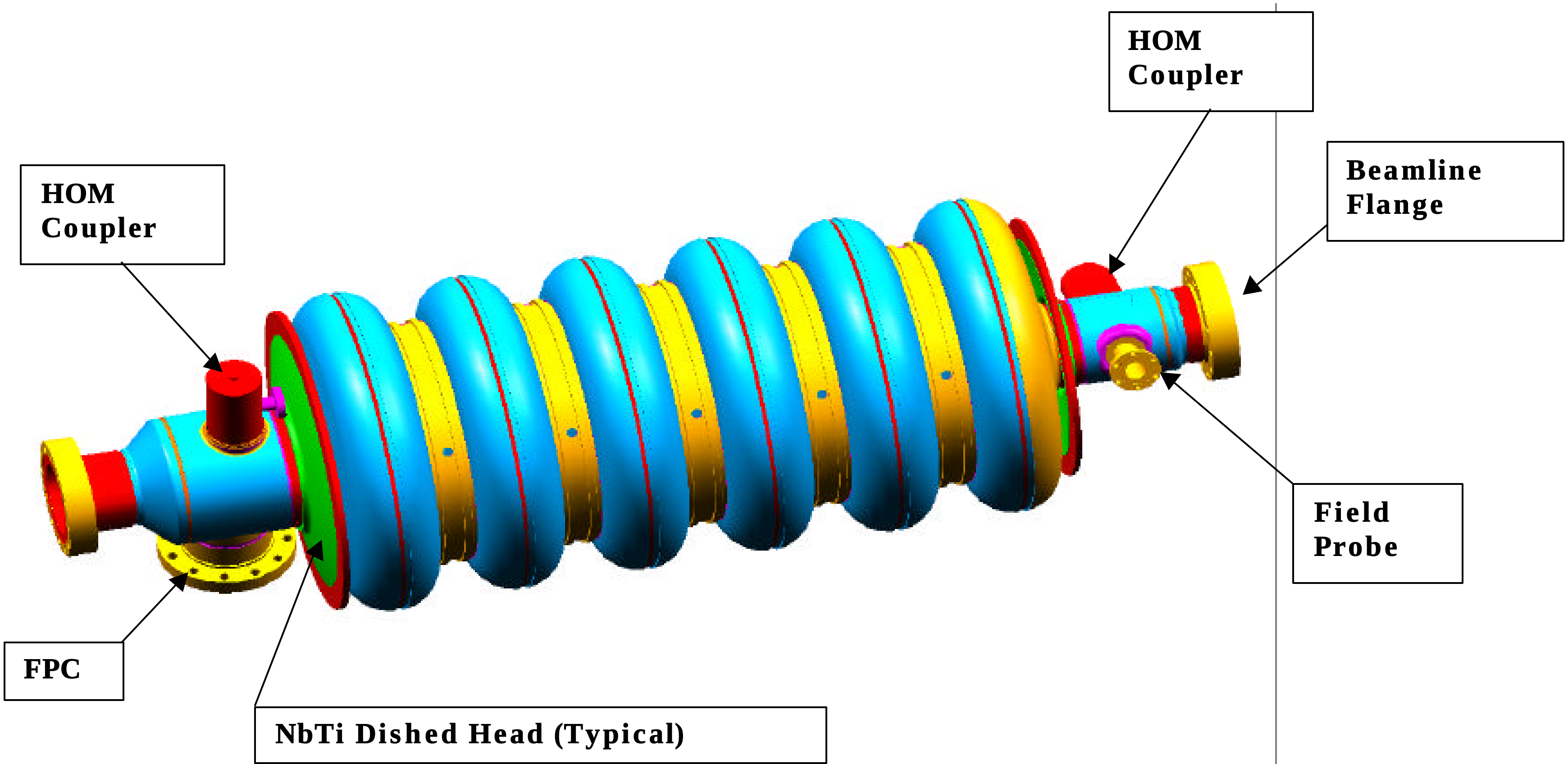
Electromagnetic/mechanical calculations by C. Pagani et al, INFN Milano, 4 die design:

E_p / E_{acc}	2.19 (2.14 for inner cell)
B_p / E_{acc} [mT/(MV/m)]	4.75 (4.58 for inner cell)
R / Q [Ω]	484.5
G [Ω]	290
K [%]	1.52
Q_{BCS} @ 2K [10^9]	37.1
Frequency [MHz]	804.979
Field Flatness [%]	1.5
Lorentz-force detuning	KL70 = -0.7 Hz/[(MV/m)^2
	KL80 = -0.8 Hz/[(MV/m)^2
	Nb thickness = 3.8 mm

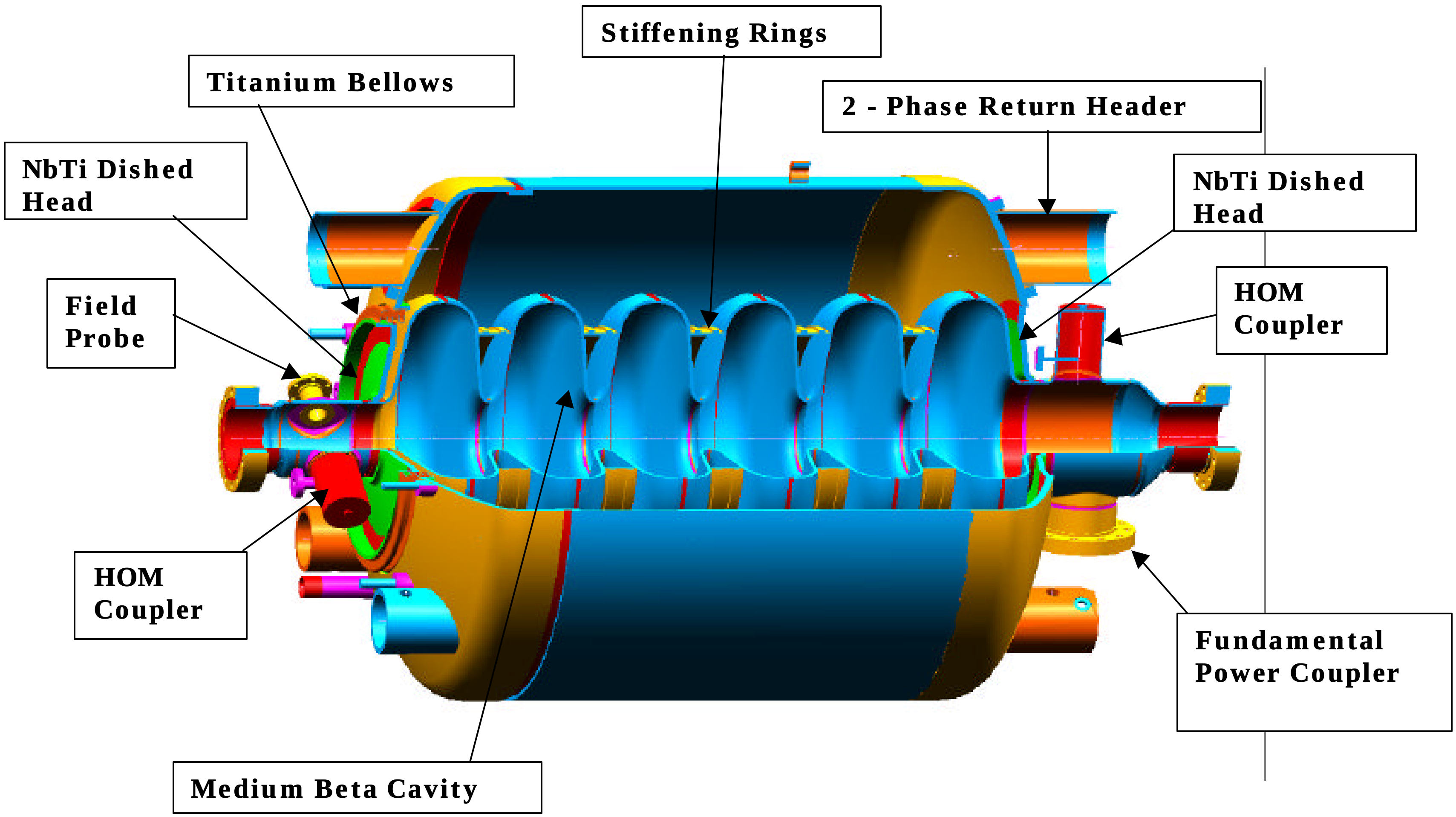
SNS High Beta Cryomodule



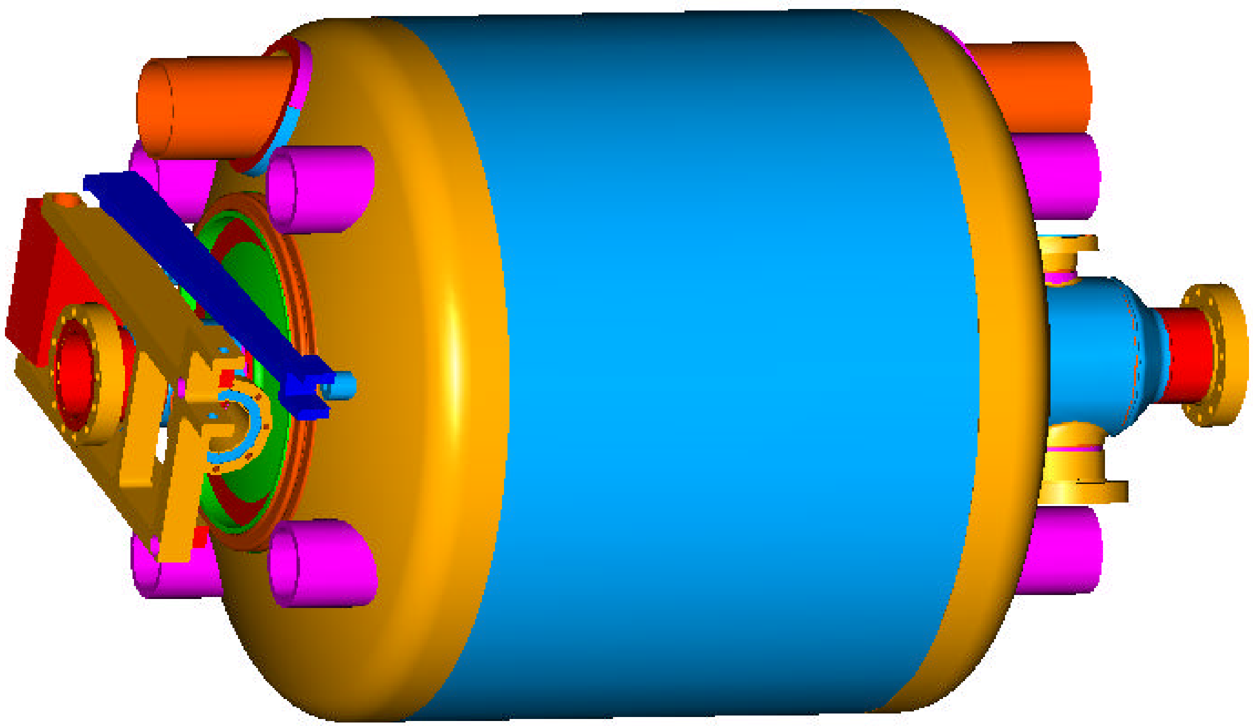
SNS Medium Beta Cavity



SNS Titanium Helium Vessel



Helium Vessel Assembly, β = 0.61 Cavity



Beta = 0.61 cavities

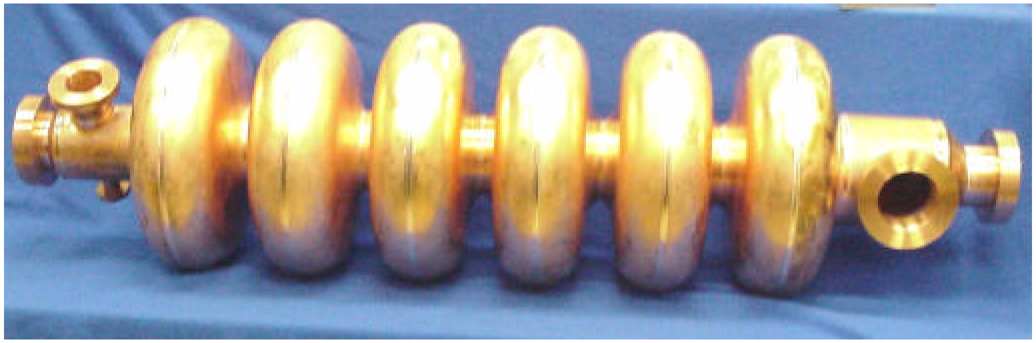
- 6-cell copper $\beta = 0.61$cavity complete
- Single cell niobium cavity for MP studies complete, tested
- 6-cell niobium $\beta = 0.61$cavity #1 complete, tested
- 6-cell niobium $\beta = 0.61$cavities #2,3,4 are 40% complete

Beta = 0.81 cavities

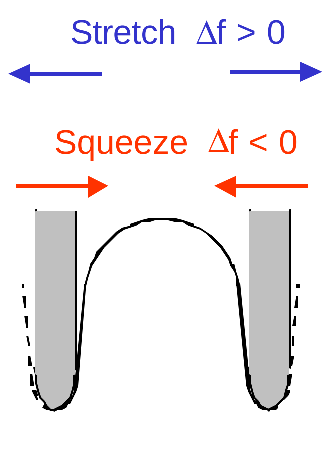
- 6-cell copper $\beta = 0.81$cavity complete
- 6-cell niobium $\beta = 0.81$cavities #5 app. 70% complete
- 6-cell niobium $\beta = 0.81$cavities #5 app. 50% complete

Copper $\beta = 0.61$

Niobium $\beta = 0.61$



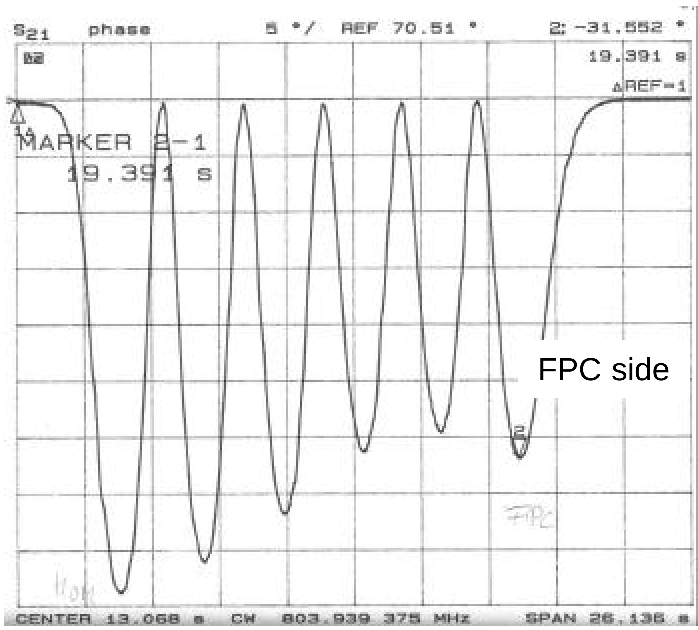
Tuning system



Tuning Code (Chen Yinghua,J.Sekutowicz,Wei Yixiang,DESY M-89-11)

- Frequency and field profile measurement of all the 6 modes of the TM_{010} pass-band
- Preparing an input file with frequency and field amplitudes at the center of the cells for each mode
- Running the tuning code developed by Jacek Sekutowicz based on a lumped-circuit model where only the coupling between neighboring cells is considered
- Obtaining the Δf to be applied to each cell to tune the cavity at the frequency requested

1 F.F.=20%

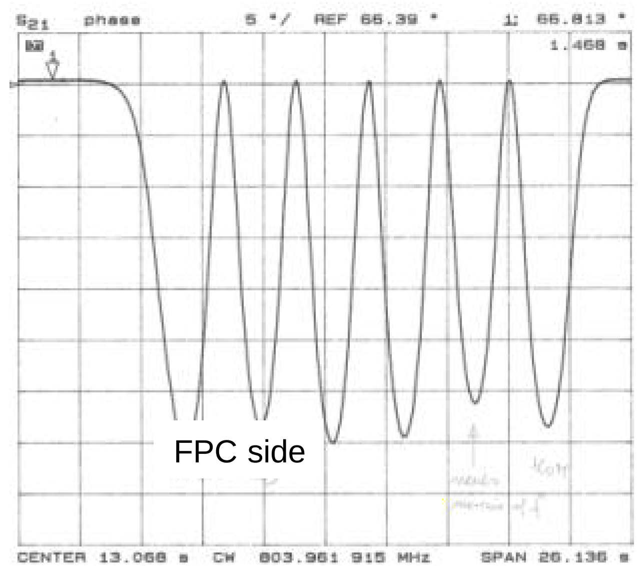


Tuning code

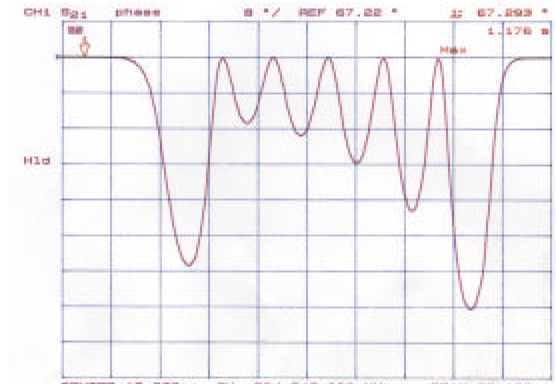
Cell #	Δf [kHz]
1	+6
2	+3
3	+68
4	+24
5	-52
6 (FPCside)	+8

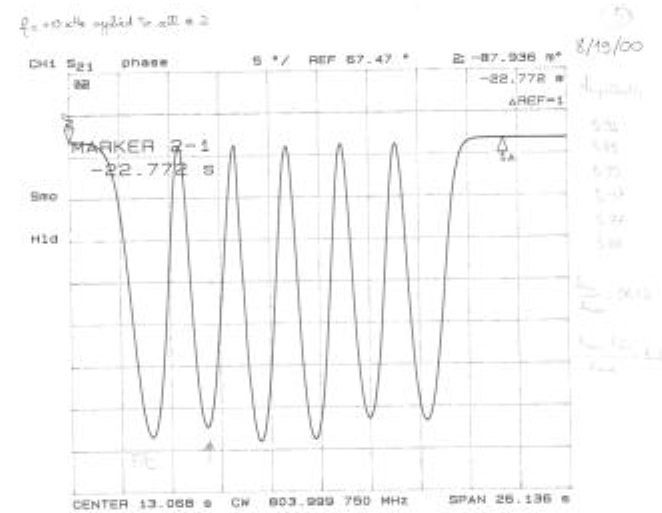
2

F.F.=6%



Cu 6 Cell Cavity





Contracts

- Niobium order for production quantity of high purity niobium placed
- Contract for 10 rf window/center conductor assemblies for the fundamental power coupler awarded
- Contract for multipacting calculations for cavities and FPC awarded
- RFP for production quantities of Nb55Ti received
- Contract for Eddy Current Scanning System awarded

Collaborations

- MOU with KEK signed
- Collaboration agreement with INFN Milan in effect
- Informal collaborations with individuals from DESY, CERN, JAERI, INFN Genoa, LANL

Cavities – Design Details

- Multipacting
- Mechanical Considerations
  - Lorentz force detuning
  - Mechanical modes
  - Stiffening, tuning
  - Yielding
- Fundamental Power Coupler
  - Doorknob
  - Window compensation
  - Multipacting
  - Q_{ext}
- Higher Order Mode calculations
  - HOM coupler design

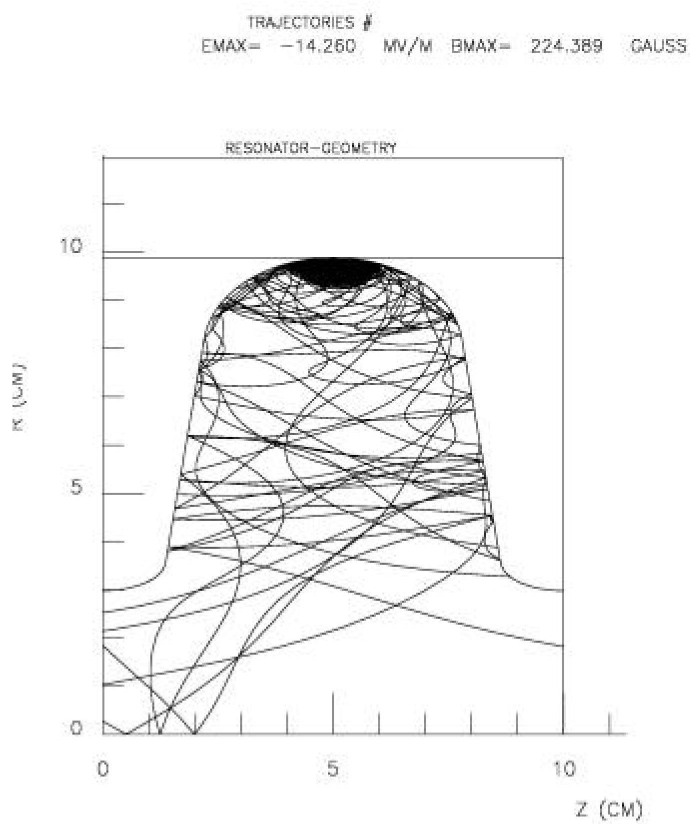
- Preliminary multipacting (MP) calculations by R. Parodi, INFN Genoa for the medium beta cavity (center cell geometry) indicated the possibility of MP levels at E_{acc} = 7.2 – 8.7 MV/m

  (2-point MP) and E_{acc} ~4.3 MV/m (1-point MP)
- Additional calculations by P.Ylae-Oijala, University of Helsinki,

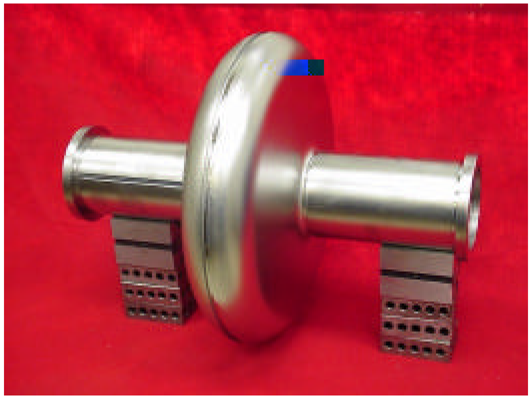
  for both beta – value, center cell and end cell geometries suggest that the impact energies of the returning MP electrons are too low to generate secondaries.(Eimp < 50 eV). However, there is a dependence of E_{imp} on the starting energy – this is being explored.
- Initial test of the single cell cavity (center cell geometry) showed

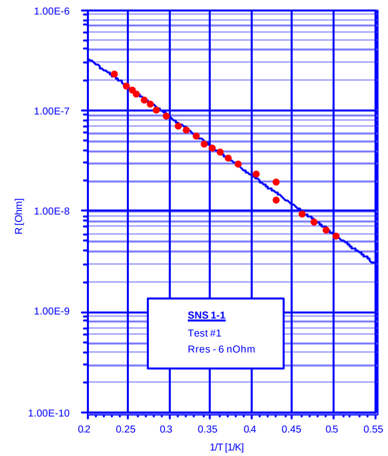
  a MP level at E_{acc} ~5 MV/m, which could be overcome easily by He-processing.

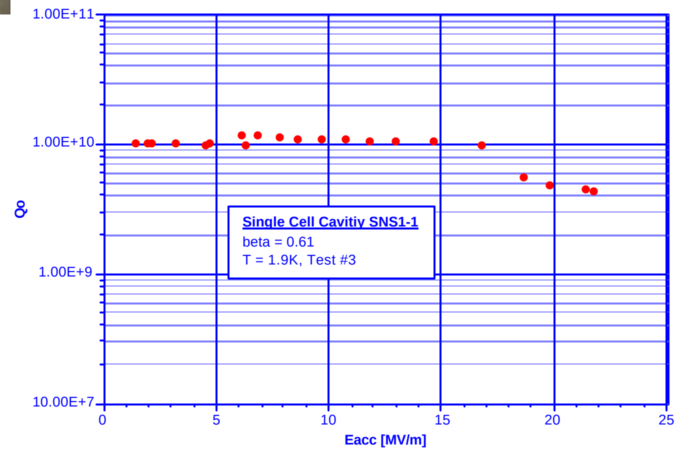
How a MP barrier looks



Cavities – Single Cell Test







Cavities - Mechanical

Calculations of mechanical mode frequencies, Lorentz force detuning, tuning forces done by D. Schrage (LANL), D. Barni (INFN), Sang-Ho Kim (SNS), K. Wilson (JLab) and N. Ouchi, (JAERI)

- Reasonable agreement on Lorentz-Force detuning
- Good agreement on mechanical mode frequencies for unstiffened cavity (42 Hz,~70 Hz and 93 Hz)
- Stiffeners at radius of 70 mm or 127 mm possible will be determined on cavity after measurements

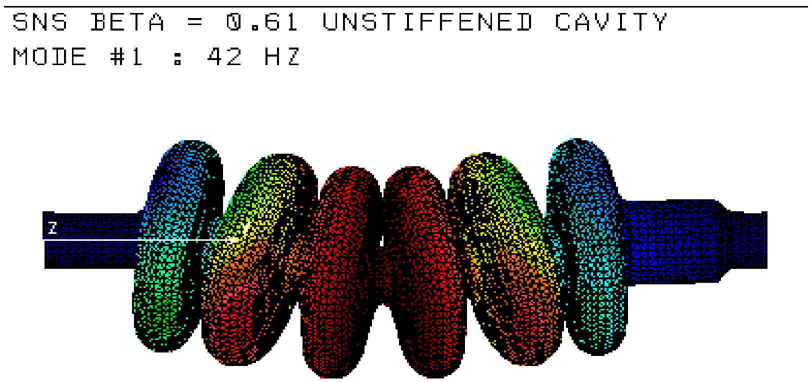
Cavities - Mechanical (cont'd)

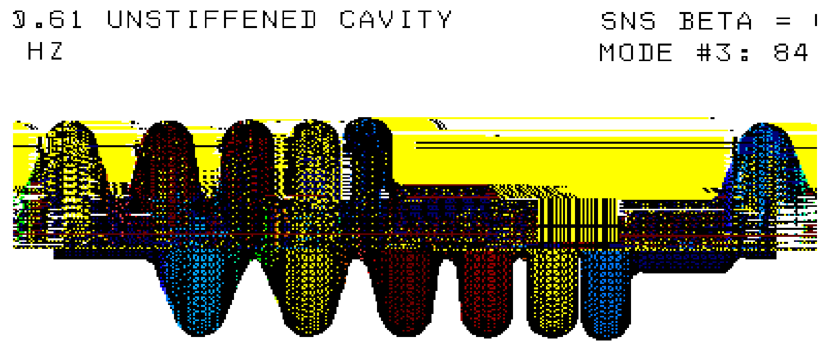
The following plan is being pursued :

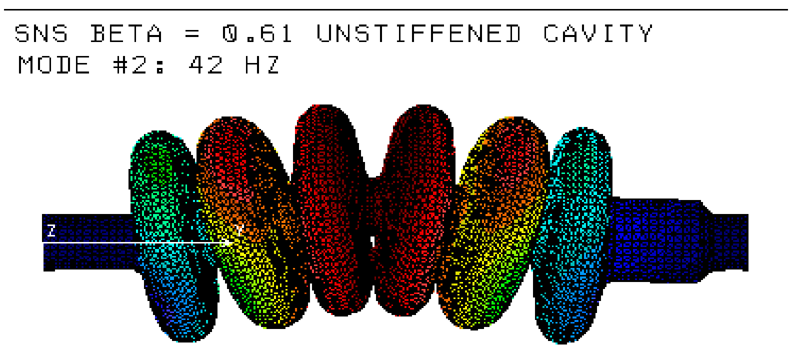
- Beta = 0.81 cavity #5 will be fabricated with stiffening rings at a radius of 70 mm
- Beta = 0.81 cavity #6 will be fabricated with stiffening rings at a radius of 127 mm
- Mechanical mode spectra and tuning forces will be measured
- Based on these data a decision will be made on the location of the stiffeners for the three Beta = 0.61 cavities needed for the cryomodule prototype

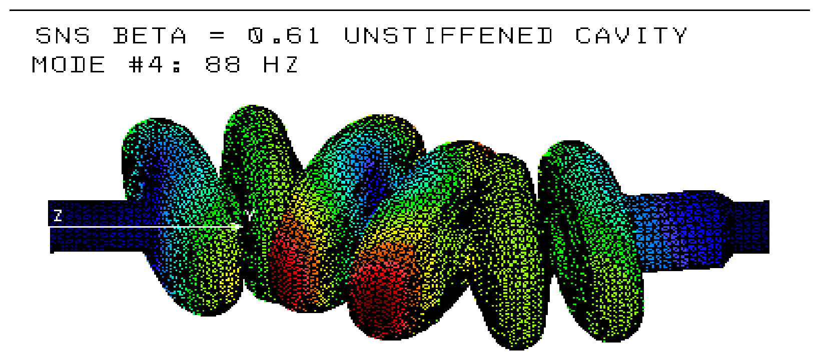
Cavities - Mechanical (cont'd)

Calculations by D. Schrage, LANL

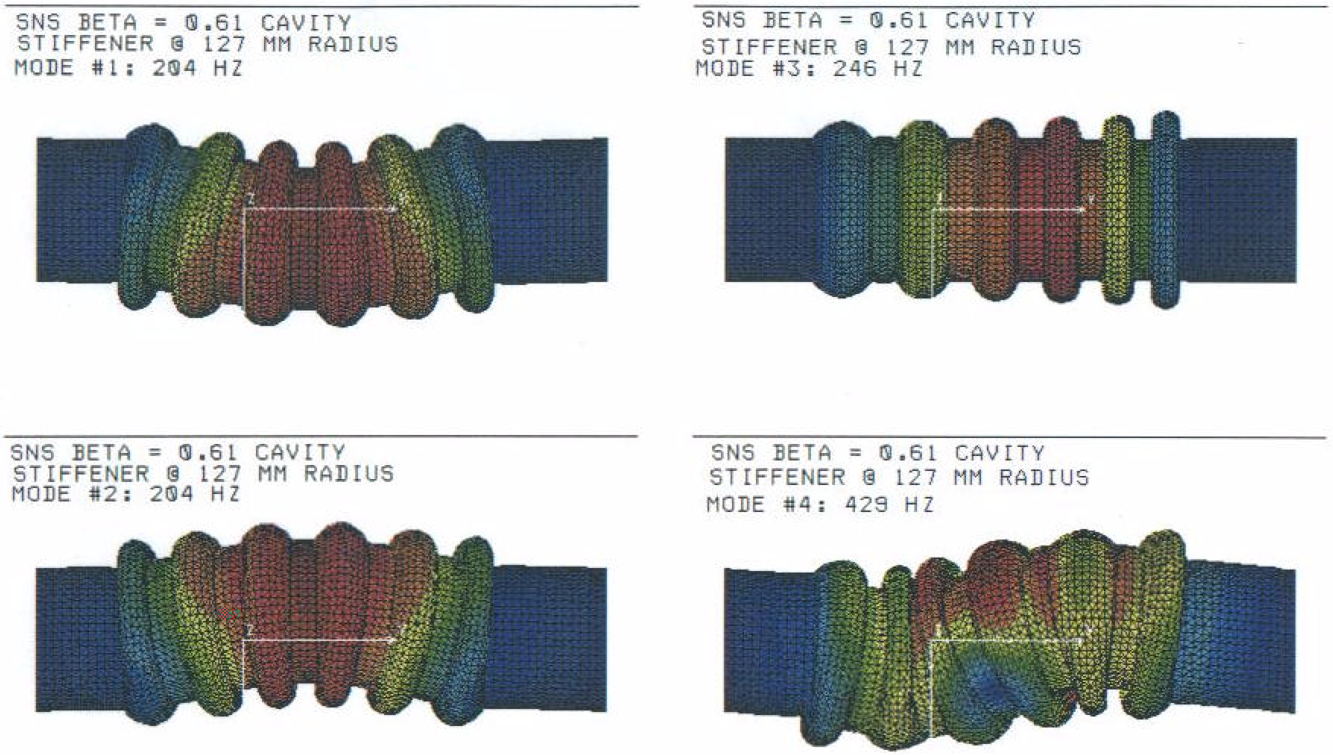






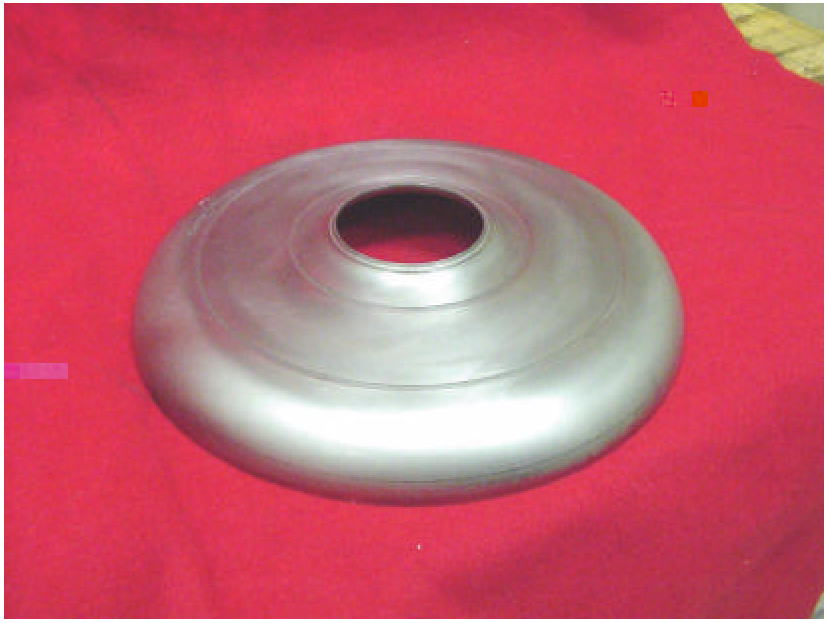


CEBAF/SNS β = 0.61 CAVITIES, Thickness = 3.8 mm



Cavities - Mechanical (cont'd)

Cavity Stiffening



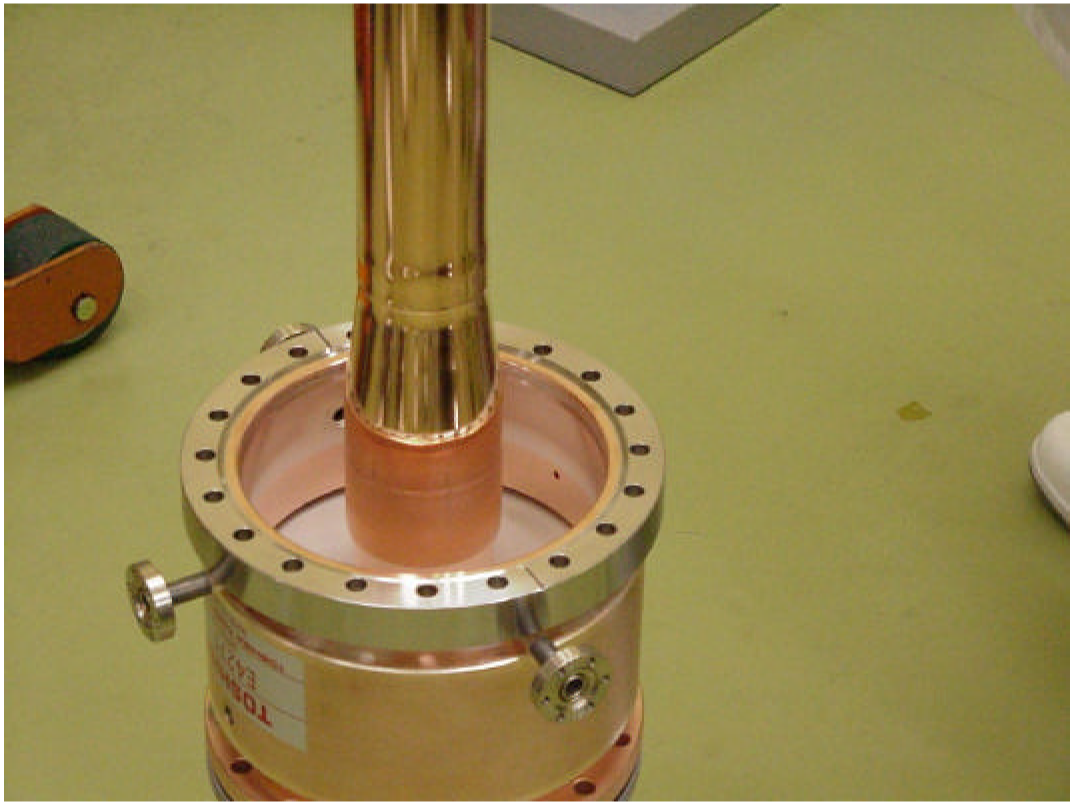
SNS Fundamental Power Coupler

- RF Power couplers have been developed by
  - DESY – TTF
  - CERN – LEP
  - LANL – APT
  - KEK – TRISTAN, KEKB
- Decision to use scaled KEK coupler for SNS was made already 1 year ago because of excellent performance with beam: 360 kW CW
- SNS coupler requirements:

app. 600 kW, pulsed, <10% duty cycle

KEK Coupler

- Design: Planar window
- Fabrication:Toshiba/MHI
- Tristan+KEKB: ~ 50



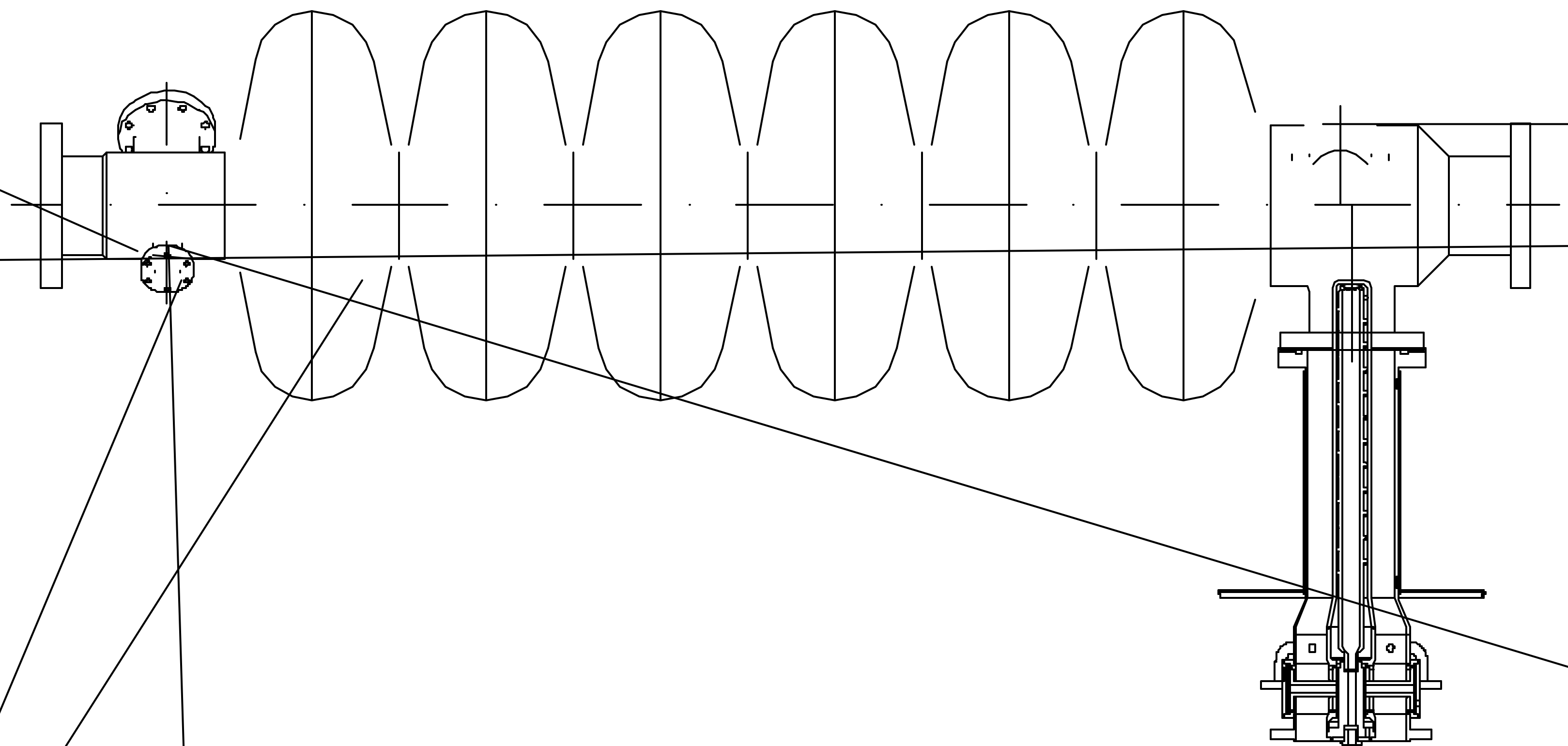
SNS Fundamental Power Coupler

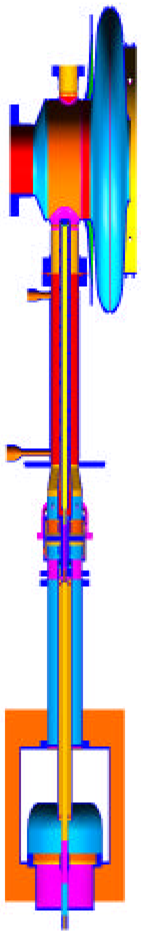
Approach to qualify coupler for SNS

- Scaling of KEK coupler with frequency
- Back the frequency scaling up with calculations for
  Doorknob geometry (Genfa Wu, JLab)
  Multipacting (Rolf Nevanlinna Institute, Univ. Helsinki)
  Window Matching (Yoon Kang, ORNL)
  Coupling Geometry/Qext (M. Doleans, Sang-Ho Kim, ORNL)
  Integration (E. Haebel, JLab)
- Qualify several companies for manufacturing of couplers

- I. Campisi, JLab, will lead the fundamental coupler activities

SNS Fundamental Power Coupler (cont'd)

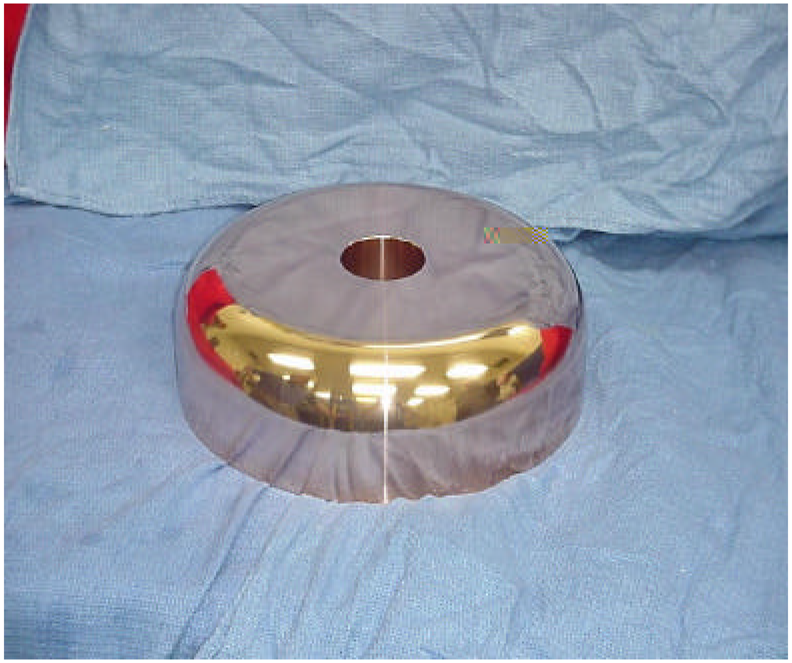


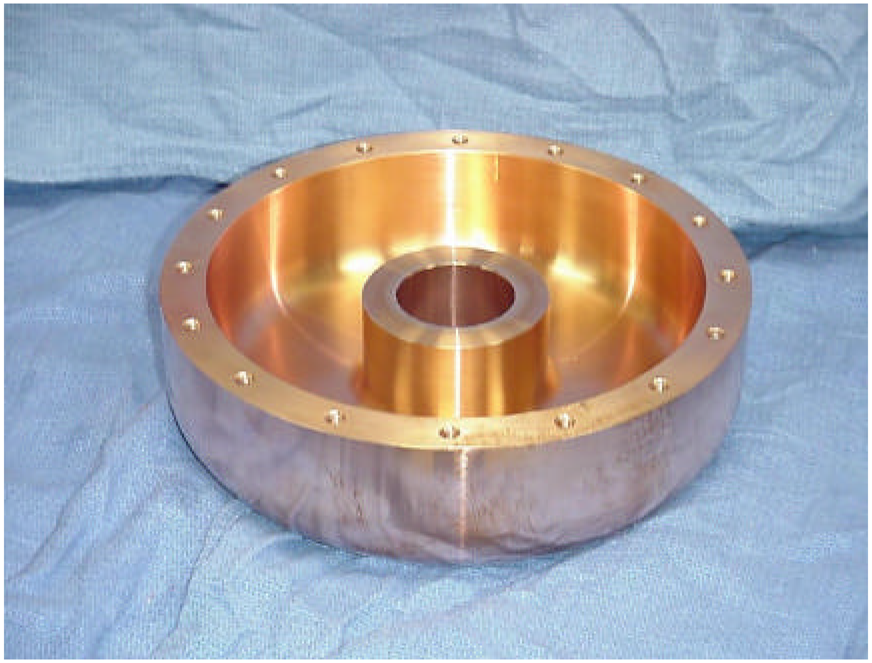


- Coupler transfers RF Power from klystron to beam
  - Normal Operation (1.0 GeV): ~400 kW at 7% Duty Cycle
  - Coupler scaled from KEKB coupler

    (508 MHz to 805 MHz)
  - Length: ~20.6 in.
  - Weight: ~23 lbs
- Ratio of inner conductor to outer conductor: 2.3 (to maintain 50 Ohm impedance)

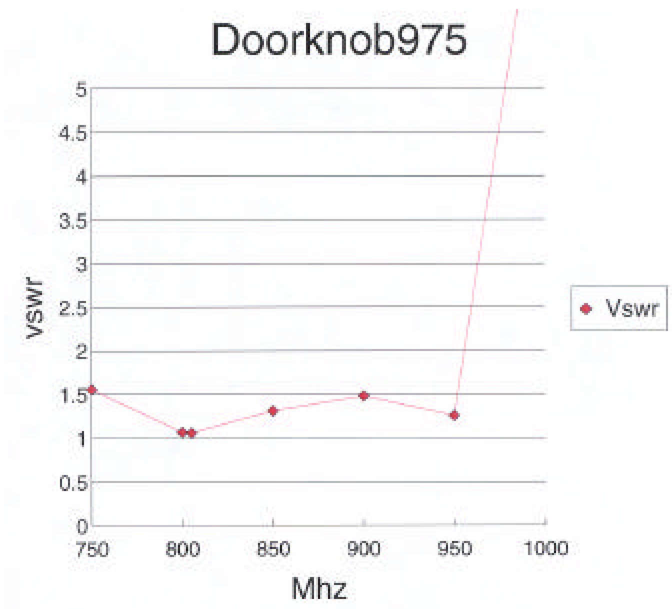
Doorknob



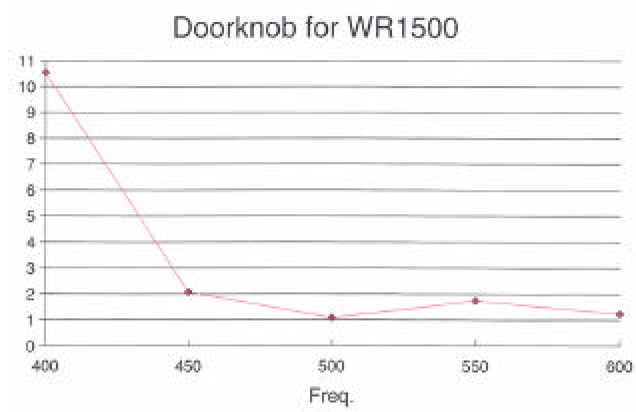


SNS Fundamental Power Coupler (cont'd)

- A doorknob transition was designed by G. Wu (JLab) using HFSS

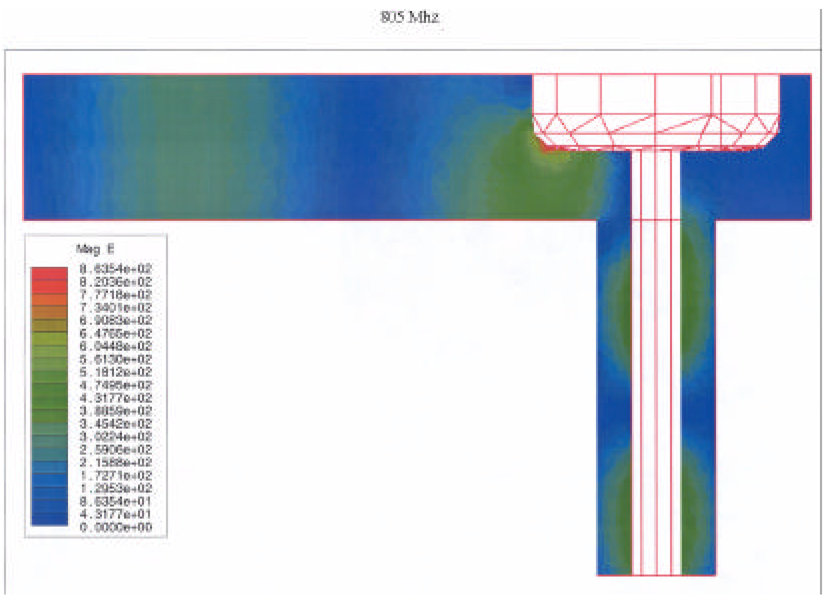


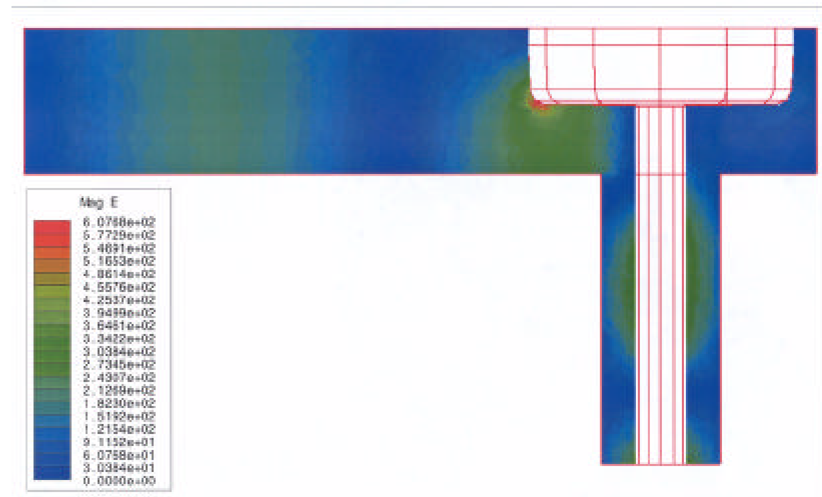
400	10.5379	0.8266577
450	2.0773	0.3500781
500	1.0753	0.0362782
550	1.7367	0.2691923
600	1.2383	0.1064592



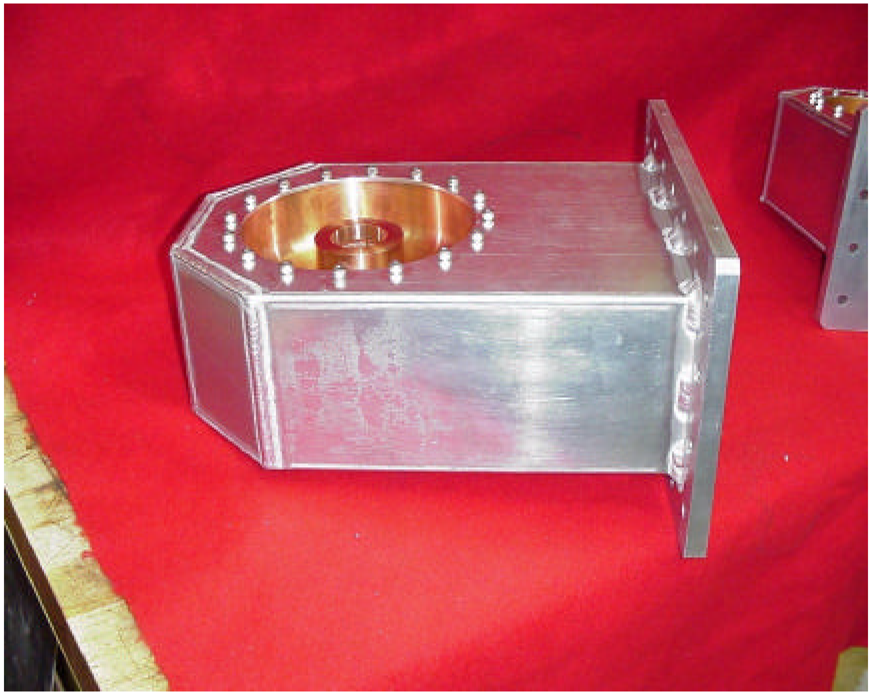
SNS Fundamental Power Coupler (cont'd)

Doorknob (cont'd),



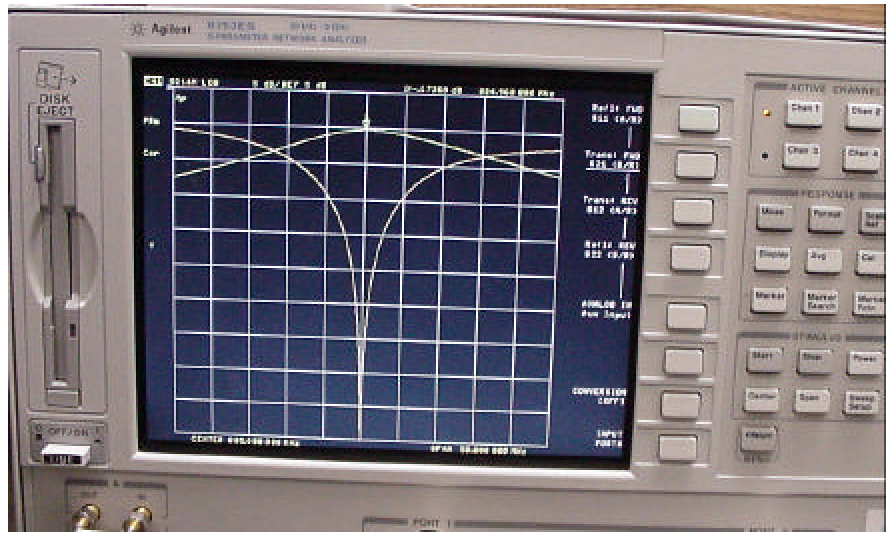


Doorknob/Waveguide Assembly



Fundamental Power Coupler

FPC Processing Test Stand



Multipacting in Couplers

e.g. P. Ylae-Oijala; "Analysis of Electron Multipacting in Coaxial Lines with Traveling and Mixed Waves", TESLA-Report 97-20

Electron Multipacting is a significant problem in coaxial lines and requires in most cases extensive "conditioning":

As in cavities, certain conditions have to be satisfied to generate multipacting:

- An electron emitted from a wall of the line is under the influence of the EM fields returning to its origin within an integer number of rf cycles
- The impacting electrons produce more than one electron, if the impact energy is high enough

Because in coax lines standing, traveling and mixed wave pattern can exist depending upon the load conditions, MP is very complex in these systems

Traveling Wave case

- Multipacting power bands occur at 4 times higher power levels than in SW case

$$P\ (TW) = 4\ P\ (SW)$$

- Only orders 2-9 multipactor because of impact energy dependence of secondary yield
- Trajectories of MP electrons are different in SW and TW operation: stationary in SW, traveling with wave in TW, app.1 mm between wall impacts

$$V(\text{traveling}) \sim d^2 f/(1+n)$$

- MP may appear in entire line in TW, only at discreet points in SW (max. of E-field)

TW/Mixed Wave case occurs, when reflected wave vanishes and is more complicated

Standing Wave case (E.Somersalo, P.Ylae-Oijala, D.Proch; "Analysis of MP in Coaxial Lines", PAC 95, pp.1500-1502)

- Multipacting always occurs close to the electric field maximum and close to zero in magnetic field: electric multipacting
- Two types of MP:
  - 1-point of different order on outer conductor
  - 2-point of different order between outer and inner conductor
- Simple scaling laws for MP in straight coax lines (f, diameter d and impedance Z)

1-point: $P \sim (f\,d)^4\,Z$

2-point: $P \sim (f\,d)^4\,Z^2$

Observations

- There does not exist a “Standard” conditioning procedure
- Each lab has developed or is in the process of developing an optimum procedure for its coupler
- Many different methods are applied in succession such as TW processing, SW (off resonance) processing, frequency sweeping, power sweeping, bias voltage processing, warm and “cold” processing, vacuum interlocking at different vacuum levels
- The objective is always to “touch” as much surface area with rf as possible to desorb residual gas layers (they enhance the secondary electron emission coefficient and cause “desorption outbursts”)

Observations (cont'd)

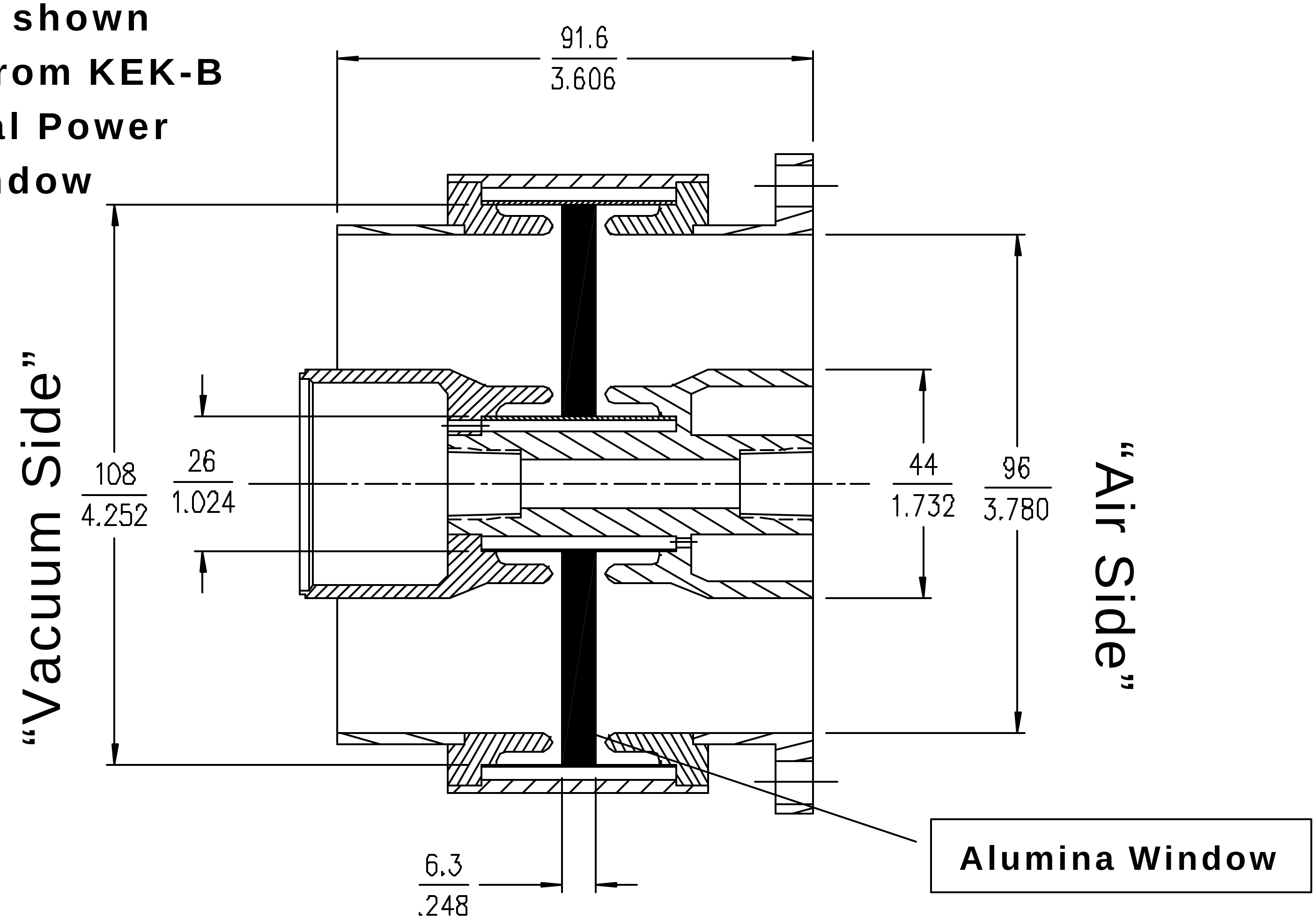
- In all cases the windows are conditioned in a test stand (or cavity) at a factor of 2 higher power levels than needed in operation
- If a cavity "quenches" in operation or trips by some other reason, all the forward power in the coupler is reflected and some areas in the coupler "see" 4 times the power level. Therefore, it seems important to "age" couplers at higher powers
- For the SNS couplers this means a rf source around 2 MW

Couplers - Test Plans

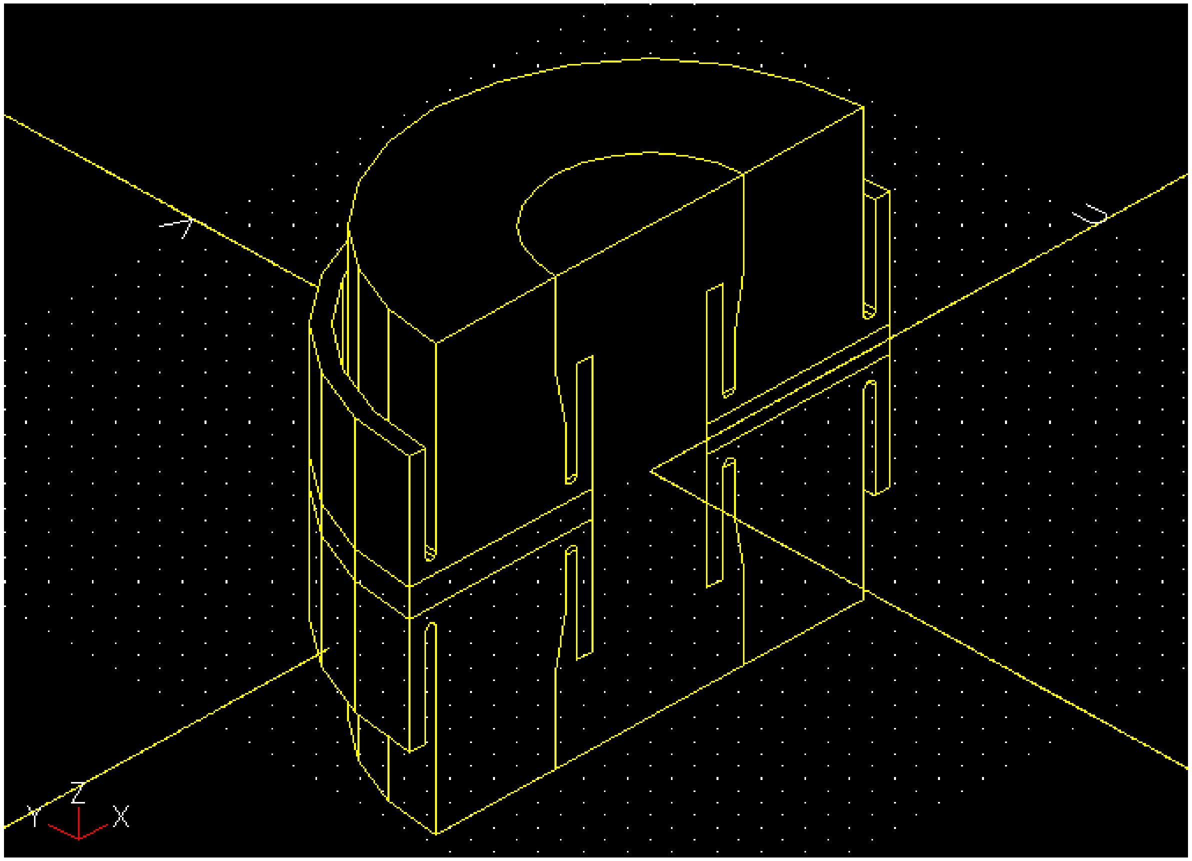
- To establish the capability to process fundamental power couplers for SNS is crucial
- Present "work-arounds" foresee processing of the couplers needed for the prototyping effort at LANL; however, this is not a satisfactory solution in the long run
- First article delivery from Toshiba of the window/center conductor assembly expected in January of 2001.
- Meanwhile a program is being developed at JLab to be ready for coupler processing: this includes design and fabrication of test stands,vacuum and interlock systems as well as procedure development for cleaning and assembly

Power Coupler Window Assembly

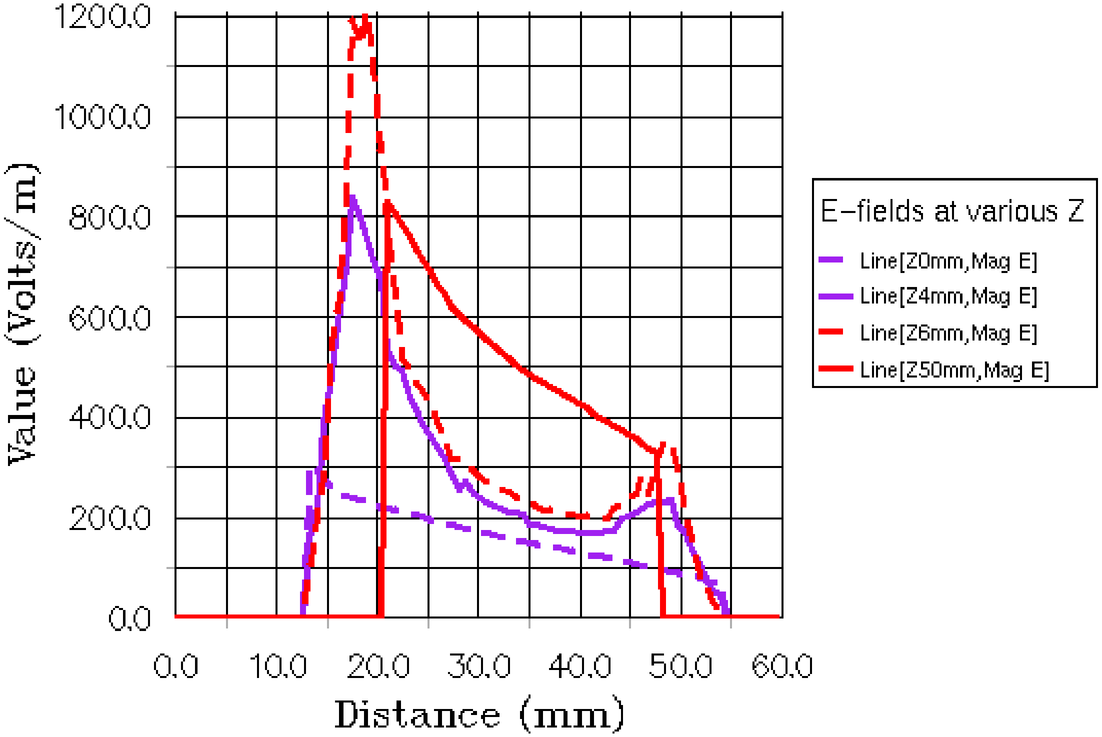
Dimensions shown are scaled from KEK-B Fundamental Power Coupler Window Assembly



Window "Matching": HFSS calculations done by Y. Kang, ORNL



SNS Fundamental Power Coupler



Comparison between KEKB window and SNS scaled model

	KEKB	SNS scaled
Frequency	508 MHz	805 MHz
Peak E-field near window	1950 V/m @ 1W	1230 V/m @ 1W
Peak E-field at Pinc	1.17 MV/m	0.93 MV/m
Insertion Loss		-0.00308 db
Return Loss	-64.2 db	-72 db

Status

- 10 Window/Center conductor assemblies on order from Toshiba first delivery of two in January 2001, testing at LANL
- Outer conductor assembly is being fabricated at JLab
- Test stand development in progress
- Two 10 kW klystrons for low power testing to arrive at JLab immediately
- Cleaning and processing procedures are being established
- Multipacting calculations are being done at Helsinki University
- A RFP for coupler prototypes has been sent to interested parties
- A coupler review is schedules for JLab on Dec. 5, ‘00

Higher Order Modes

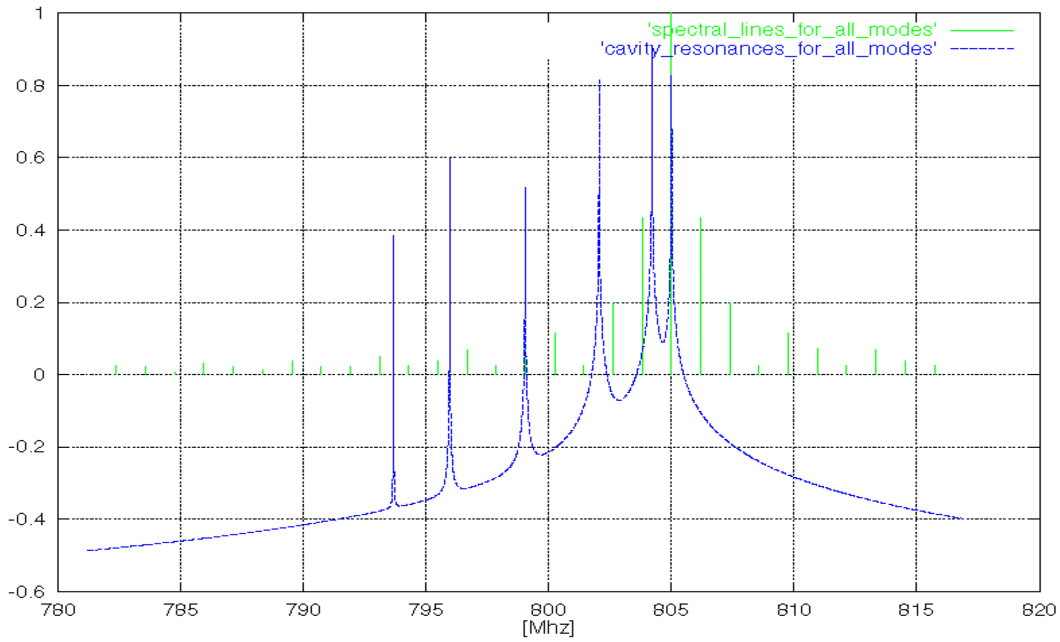
- Jacek Sekutowicz , DESY and Sang-ho Kim/Marc Doleans, ORNL have carried out HOM calculations for monopole ,dipole, quadrupole and sextupole (longitudinal, transverse) higher order modes using different codes

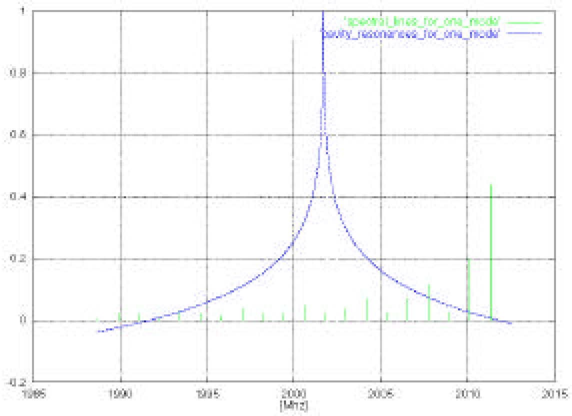
- The agreement is quite good.

- Some of the calculations by Jacek Sekutowicz indicate that some modes fall on machine lines (multiple of 402.5 MHz) with non-negligible R/Q – values

- Some HOM's are concentrated near the center of the cavities, others are shifted to the beam pipes

- Fundamental passband modes are "reasonably placed" on spectral lines; 3. mode is at spectral line (J. Sekutowicz)

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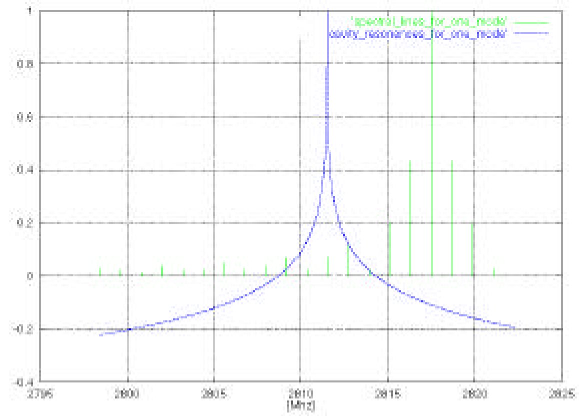
[Mhz]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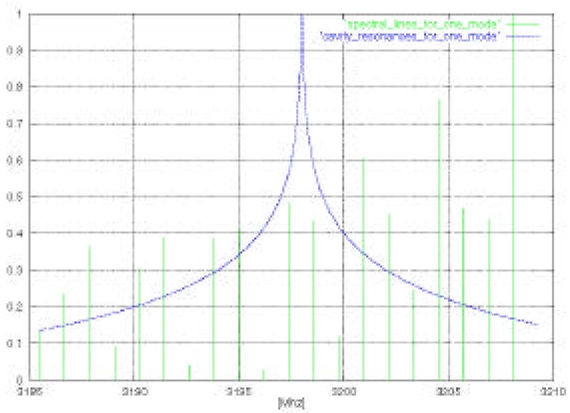
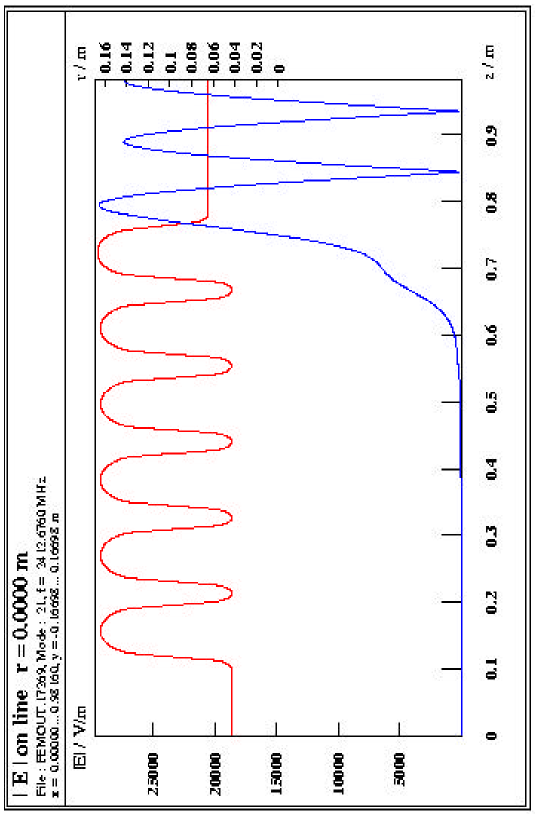
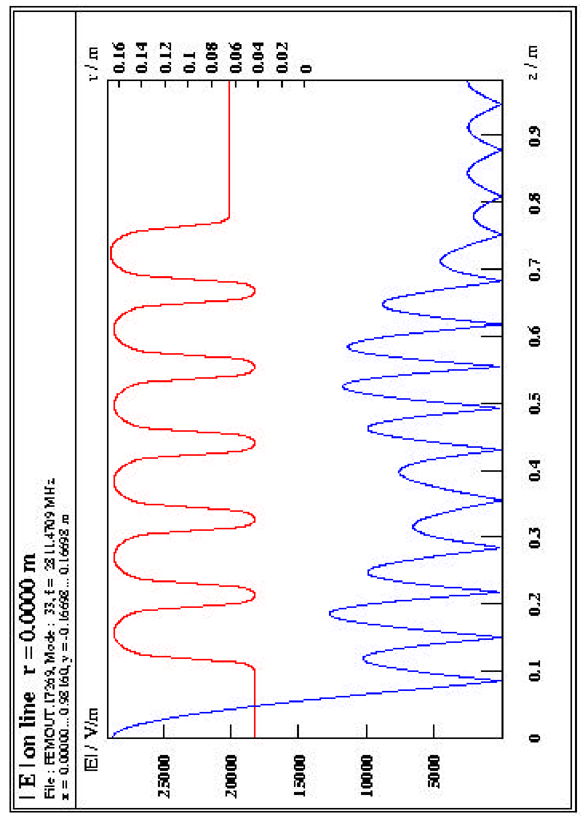

'spectral_lines_for_one_mode'
'cavity_resonances_for_one_mode'
[Mhz]

HOM at 2411 MHz



HOM at 2811 MHz



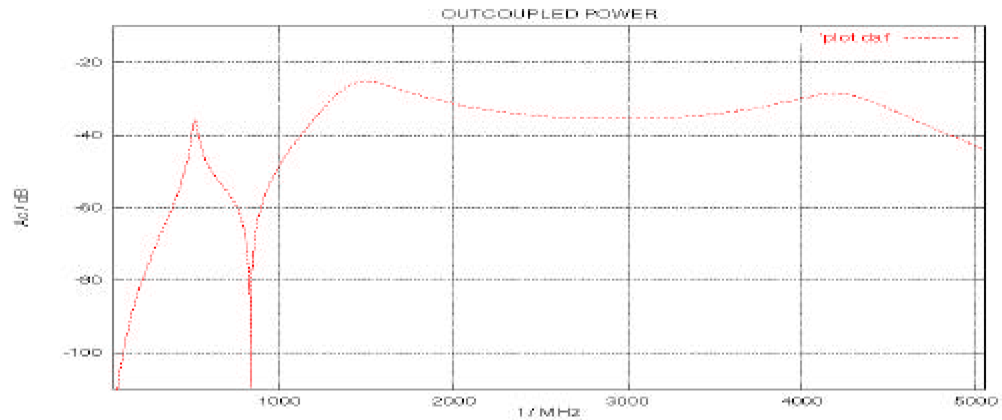
Subsequently, beam dynamics calculations have been carried out by R. Sundelin, JLab and Dong-o Jeon, Sang-ho Kim and Marc Doleans, ORNL to determine the need for HOM-couplers and/or the magnitude of the Qext-values, to which the HOM's have to be damped to avoid beam instabilities and power deposition into the Helium bath.

The results can be summarized as following:

- Neither tranverse nor longitudinal beam instabilities occur in the $\beta = 0.61$ cavities, if the Q-value is $<10^8$ and the frequency spread is >20% of the expected spread due to manufacturing variations

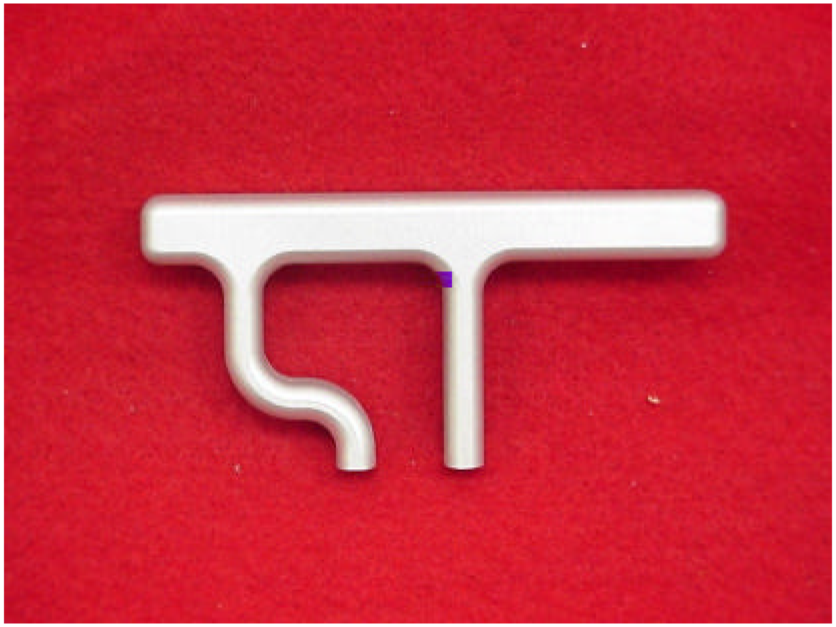
- For about 6 modes there is significant power generated depending on the Q's of the modes; the amount of power can be readily extracted from the cavities

Higher Order Mode Coupler•HOM Coupler was designed by J. Sekutowicz, DESY



Higher Order Mode Coupler (cont'd)

HOM Coupler was designed by J.Sekutowicz, DESY



Higher Order Modes

- The production cavities for SNS will have welded on HOM coupler of the DESY/Saclay type

- A prototype single cell niobium cavity is being build with welded on couplers to evaluate the damping of the various higher order modes, the filter characteristics after chemical surface treatment

  and the cavity performance

- Prior to complete fabrication of the niobium model a copper model will be used for room temperature measurements

Final Cavity Review

A final review of the cavity design prior to issuing a RFP in early December 2000 was held September 20, '00 at JLab. The report of the review panel consisting of 7 experts in the field come to the following conclusions:

- They were quite impressed by the progress made since the start of the activity in late April
- They thought that obviously tests of the 6-cell cavities need to be made to confirm that design performance of the cavities can be met
- The number of HOM couplers and field probes should be determined
- The issue of stiffening of the cavities need to be re-examined
- They approved the presented Helium vessel design; procurement will proceed

Cavity Review

- One of the recommendations of the review committee has been met meanwhile: the 6-cell beta = 0.61 cavity has been tested
- Preliminary test results are:

$E_{acc,\,max}$ ≥ 11 MV/m

Q (2.1K, $E_{acc,\,max}$) = 7 x 10^9

R_{res} = 5 nΩ

$\Delta f/\Delta p$ = 326 Hz/torr

k = 20 Hz/(MV/m)^2

6 cells b=0.61 cavity SNS6-1

Q_0 vs. E_{acc}